Confinement of Higgs bosons from hidden symmetry and convexity

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Abstract

In the full effective potential (EFP) approach, we find that spontaneous symmetry breaking (SSB) can, with the convexity of the full EFP, lead to the prediction of the IR confinement of Higgs particles, adding difficulty to the experimental identification of Higgs particles. The short distance behaviors remain intact. The whole presentation is given in the understanding that any QFT becomes UV well defined in a more complete underyling theory according to a recently proposed strategy.

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1 Introduction

The standard model of particle physics within the contemporary experiments' range has been deemed as well established. Precision tests of standard model have been the main activities of the particle physicists [1]. However, there are still some issues remaining unclear in the standard model, the most important one is the electroweak symmetry breaking and the Higgs mechanism–an aspect that is still mysterious and less understood. Many variants and/or improvements with respect to this vital sector of standard model have been proposed and discussed, among them there are two basic types, one in terms of elementary scalar fields or one in terms of composite Higgs fields. Recently some authors even try the alternative electroweak symmetry breaking mechanism following the tricks derived from the SUSY and string studies [2].

In this report we wish to study the spontaneous symmetry breaking (SSB) phenomenon within the conventional quantum field theory frameworks together with a new strategy to deal with the possible UV unphysical infinities. We also wish to call attention to the utility of the (exact) effective potential (EFP) of a QFT via the demonstration of its role in SSB. This article is an extended report of the recent suggestion by the author [3] where we made crucial use of the convexity of the full EFP [4] as well as the fact of SSB [5].

The article is organized as follows. We discuss some properties and disputes about the EFP method in section II, especially the convexity and utility of the full EFP and effects of renormalization. We will give a descussion basing on our recently proposed strategy for calculating quantum contributions. Section III is devoted to the derivation of the properties of the Higgs system in terms of the full EFP. We only assume SSB mechanism and the convexity for the EFP of the Higgs system without specifying spacetime dimension and the other physical sectors of the system. Thus our conclusions will not be limited to specific models. The main technical observations are given in section III. The other implications and discussions will also be given there. In section IVwe make a digression on the triviality problem. The last section will be a brief summary.

2 Convexity of EFP

First we need to discuss some properties of the main tool we are going to use, i.e., the EFP that is also known as the generating functional for one-particle-irreducible(1PI) Green functions [6] for constant field configurations or *in infrared limit*.

It is known that the full EFP is real and convex for any QFT within which it can be consistently defined [4]. However, due to UV divergences, one might wonder if renormalization could violate the convexity and there has been a lot of literature investigating this impact [7, 8]. We will follow the standard point of view that renormalization would not affect the convexity provided it is appropriately done [7]. In fact, as will be demonstrated shortly, if one adopts a natural strategy to deal with the UV infinities [9], the convexity would naturally follow.

In practical calculations people often arrive at nonconvex and complex effective potentials, which seems to be in conflict with the above assertion. The solution lies in that the full EFP is complex where it is nonconvex [10, 8]. The imaginary part arises if one starts from perturbative definition of the EFP where the parameters (masses, couplings, etc.) are defined in the contex of a nonconvex local lagrangian (not an IR object), i.e., defined in a formulation where the field configurations (or states) are not all stable ones. It is shown by Weinberg and Wu [10] that this imaginary part multiplied with the space volume is half the decay constant of the unstable modes. Orthodoxically the arguments of EFP are not expectation values in localized (homogeneous) states but that of superposition of distinct states in the nonconvex region [10, 8, 11].

In this report, however, we follow a somewhat unorthodox line of argument. It is known that the Landau-Ginsurg model is a phenomenological and nonconvex model [12]–merely a simple polynomial potential in terms of a few phenomenologically-defined coefficients. There are some ingredients in this model that are not thermodynamically stable. Similar thing happens in the van der Waals theory. Now we ask the following question: what will the complete and thermodynamically stable formulation look like? The answer will be a consistent formulation with all thermodynamically unstable states removed and convex thermodynamic potentials [13] will naturally follow from the very thermodynamical stability. In the quantum field theory with a nonconvex phenomenological lagrangian, one would naturally ask: **what are**

the final outcome of the decay indicated by the imaginary part? For the decay to stop with the imaginary part gone, the final outcome will necessarily be a formulation containing only stable modes or states, then there should be no imaginary and/or nonconvex parts for the full EFP at all and no general obstacle to interpret the EFP as mininal energy functional for homogeneous field expectation values as IR limit of the full effective action.

There remains one issue to be addressed, the meaning of any possible flat bottom of the EFP. Since the full EFP should have taken in the all quantum effects, this region is effectively isolated in the large distance from all the other part where the EFP is not flat (Cf. section III). This is an alternative way of securing the stability of the physical vacuum. Conventionally, one would resort to a nonconvex lagrangian and define the qunatum theory around a local minimum to stablize the theory. But an imaginary part would necessary appear. So unlike the orthodoxical point of view that the convex EFP is not quite useful, our unorthodox arguments shows that the convex EFP is informative provided it is understood as defined in the context without unstable modes. More conservatively, we are trying an interpretation of the flat bottem so that the convex EFP might still be physically useful.

Hence, to get a real and convex full EFP, the qunatum theory should be formulated in terms of stable field configurations and states. (Here we emphasize that this convexity of the full EFP does not necessarily mean that the short distance structures of the theory should also be simply described by a convex microscopic model as the EFP is only a meaning full object in the IR limit.) It is a demanding job to find such a formulation, which might be a very complicated quantum theory. For our purpose here, we only need to assume that such a formulation exists (the SSB (scalar) sector will still be named as the Higgs sector but without the nonconvexity in the original Higgs model[14]).

Now we serve the simple proof of the convexity of EFP following our strategy for calculating the quantum corrections proposed by the author [9]. In our proposal, we can view a conventional QFT of standard model as an ill-defined (due to UV and/or IR divergences) effective sector of a complete and well-defined underlying theory. In the underlying theory the path integral of the QFT should read (to shorten the presentation we only write out the SSB sector with the other parts either integrated out or kept external for

appropriate purposes)

$$Z_{\{\sigma\}}(J) = \int D\mu(\phi_{\{\sigma\}}) exp[i\{S_{\{\sigma\}}(\phi_{\{\sigma\}}) + (\int J * \phi_{\{\sigma\}})\}] \qquad (1)$$

where J denotes the external sources (spacetime dependence is understood here), the subscript $\{\sigma\}$ refers to the underlying structures and it is used to indicate that Higgs fields and the action are effective objects in the sense of the underlying theory. This functional is by postulate well defined and the path integration can be done. Since the underlying structures are infinite comparing to the effective objects, a limit operation is triggered on the functional and therefore the functional would be given in term of the low energy parameters and some possible finite constants (arising from the limit operation) in place of divergences. It is illegitimate to simply perform the limit operation first since the path integration and limit operation do not always commute. Otherwise, divergences would show up. With this observation, a simple strategy for calculating loop corrections without knowing the exact underlying structures follows naturally and it applies to any physically meaningful model (renormalizable or not), see Ref. [9]. Note again, it is understood that the effective formulation thus obtained is free of any unstable ingredients.

Due to the arguments given above, we have

$$Z(J;\bar{c}) \equiv exp[iW(J;\bar{c})] = L_{\{\sigma\}} Z_{\{\sigma\}}(J) \equiv L_{\{\sigma\}} exp[iW_{\{\sigma\}}(J)], \qquad (2)$$

where W refers to the connected functional and $\bar{c}$ are the finite constants arising from the limit operation. In conventional renormalization programs, one introduces some regularization acting as artificial substitute for the true underlying strutures and later performs subtractions to remove the artificial structures. However, in our point of view one must be careful about this artificiality and subtractions as is evident from the explicit existence of the constants $\{\bar{c}\}$ in Eq.(2). Without knowing the underlying structures we have to resort to appropriate physical principles and experimental facts for relevant physics for defining these constants. Here it suffice to assume that we can define the constants in the way equivalent to the underlying theory defintion.

Now let us perform the Legendre transform on the connected functionals to find the effective actions or the generating functionals for 1PI Green functions. Then there are two such generating functionals, one with underlying

parameters and one with the constants $\bar{c}$ instead:

$$\begin{aligned}\Gamma_{\{\sigma\}}(\phi_{\{\sigma\}}) &\equiv LgT[W_{\{\sigma\}}(J)] \equiv Min_J\{\int \phi_{\{\sigma\}} * J - W_{\{\sigma\}}(J)\} \\ &= \int \phi_{\{\sigma\}} * J^0 - W_{\{\sigma\}}(J^0), \quad \phi_{\{\sigma\}} \equiv \frac{\delta W_{\{\sigma\}}(J^0)}{\delta J^0}; \qquad (3) \\ \Gamma(\phi;\bar{c}) &\equiv LgT[W(J;\bar{c})] \equiv Min_J\{\int \phi * J - W(J;\bar{C})\} \\ &= \int \phi * J^0 - W(J^0;\bar{c}), \quad \phi \equiv \frac{\delta W(J^0;\bar{c})}{\delta J^0}. \qquad (4)\end{aligned}$$

Note that by definition the effective action is defined at a functional point J^0 that maximizes W. Since the Legendre transform LgT and the limit operation $L_{\{\sigma\}}$ apply to different arguments and all the objects here are well defined, we have

$$[LgT, L_{\{\sigma\}}] = 0, \qquad (5)$$

$$\Gamma(\phi;\bar{c}) \equiv L_{\{\sigma\}}\Gamma_{\{\sigma\}}(\phi_{\{\sigma\}}), \quad \phi \equiv L_{\{\sigma\}}\phi_{\{\sigma\}}. \qquad (6)$$

Now it is straightforward to see that the effective action is a concave functional due to definition in Eq.(3), i.e.,

$$\frac{\delta^2\Gamma_{\{\sigma\}}}{\delta\phi_\sigma(x)\delta\phi_\sigma(y)} = \frac{\delta J^0_x}{\delta\phi_\sigma(y)} = \{\frac{\delta^2 W_{\{\sigma\}}(J^0)}{\delta J^0_x \delta J^0_y}\}^{-1} \leq 0. \qquad (7)$$

Note that the nonpositive second order functional derivative only symbolically inidcates that $J^0(x)$ maximizes W. Applying the limit operation to Eq.(7) would lead to the same conclusion for $\Gamma(\phi;\bar{c})$. One can also use Eq.(4) to prove its concavity (in the functional sense):

$$\frac{\delta^2\Gamma(\phi;\bar{c})}{\delta\phi_x\delta\phi_y} = \frac{\delta J^0_x}{\delta\phi_y} = \{\frac{\delta^2 W(J^0;\bar{c})}{\delta J^0_x \delta J^0_y}\}^{-1} \leq 0. \qquad (8)$$

Again the inqeuality takes a symbolic meaning. Then the EFP for constant ϕ reads

$$U_{eff}(\phi;\bar{c}) = -\Omega\Gamma(\phi;\bar{c}), \qquad (9)$$

$$\phi(x) = const., \quad \Omega \equiv \int d^n x \qquad (10)$$

and the EFP's convexity follows as a consequence of the fact that the effective action is a concave functional. In the course of the derivation the constants $\bar{c}$ do not make any trouble once they are consistently defined. As the orthodox renormalization procedures just amount to afford definitions for these constants, we conclude that consistent renormalization programs would not violate the convexity of the full EFP in renromalizable models. If one adopts our approach, the conclusion applies to any model with consistent definitions for $\bar{c}$ implementable.

In the following we will not label out the constants $\bar{c}$. But the flavor degree will be labelled out where necessary.

3 Hidden symmetry and confinement of Higgs fields

Now let us write down the convexity relation as

$$\partial_{\phi_i}\partial_{\phi_j}U_{eff}(\phi) \geq 0, i,j = 1,\cdots,N \tag{11}$$

with the N-Flavor index denoted by i,j.

Then the SSB on flavor symmetry can be stated as: $U_{eff}(\phi)$ is invariant under the action of the symmetry group G_{flavor} while the vacuum state $|0\rangle$ is not, that is to say

$$\hat{U}(g)|0\rangle \neq |0\rangle \, , g \in G_{flavor} \tag{12}$$

with $\hat{U}(g)$ denoting the unitary representation of the group G_{flavor} in QFT and $\phi_{vac} = \langle 0|\hat{\phi}|0\rangle(\neq 0)$ minimizes $U_{eff}(\phi)$:

$$\partial_{\phi_i}U_{eff}(\phi) = 0, \quad \partial_{\phi_i}\partial_{\phi_j}U_{eff}(\phi) \geq 0 \tag{13}$$

in a small neighborhood of ϕ_{vac}, or equivalently

$$U_{eff}(\phi) \geq U_{eff}(\phi_{vac}), \qquad \forall \phi \tag{14}$$

while the degeneracy of the vacuum state indicates the existence of Goldstone modes [15].

Now combining Eqs. (13),(14) and (11), it is very easy to conclude that the EFP must have a flat bottom, i.e.,

$$U_{eff}(\phi) \equiv U_{eff}(\phi_{vac}), \quad \forall \phi \in \bar{A} := \{\phi : |\phi| \leq |\phi_{vac}|\}. \tag{15}$$

Then obviously,

$$\Gamma^{(n)}_{i_1\cdots i_n}(0,0,\cdots,0) := \partial_{\phi_{i_1}}\cdots\partial_{\phi_{i_n}}U_{eff}(\phi) \equiv 0, \quad \forall n \geq 1, \qquad (16)$$
$$\phi \in A^0 := \{\phi : |\phi| < |\phi_{vac}|\}$$

while $\Gamma^{(n)}_{i_1\cdots i_n}$ could not vanish identically outside the set A^0 for at least $n = 2$, which is the two-point 1PI Green function at zero momentum—the effective mass, then there must be at least one index i_0 such that $\partial^2_{\phi_{i_0}}U_{eff}\,|_{\phi=\phi_{\mathbf{vac}}} > 0$ otherwise all fields would be massless ones which is certainly not the case in SSB sector. Then we immediately have

Proposition I

The full effective potential for the Higgs model with SSB could not be expanded into analytical Taylor series around the vacuum state or any state degenerate with the vacuum. In other words, the Higgs sector (SSB sector) is singular in the IR limit.

Since $\Gamma_{i_1\cdots i_n}$ assume effective interactions **in the IR limit**, it follows immediately that in the IR limit and without gravitation the sector $\mathring{A}$ is a totally free sector with only massless states and each state (modulo degeneracy) in this sector is isolated with any other one (including states beyond A^0) due to the absence of effecitve interactions. Of course the standard model could not stand on any state in this massless sector but only be established on the physical vacuum state ϕ_{vac} that could not transit into the $\mathring{A}$ sector. This is just the mechanism assuring the stability of the physical system realized in the context of convex full EFP in the unorthodox reasonings advocated in section II. Note that the IR singularity predicted here for the SSB sector is a genuine physical property of the theory. We may associate discontinuity in the effective vertices with phase transition behavior, with Higgs fields acting as order parameters. Then the phase transition is a second order one. Thus the convex EFP (or stable formulation) is not uninformative. It is important to recall that the derivation here is based on the full theory, not perturbative approximation, and hence effective vertices and their generating functional are nonperturbative objects.

Since Proposition I tells us that we can not Taylor expand the full EFP around the vacuum, this immediately implies that the effective couplings for the Higgs modes that breaks the flavor symmetry spontaneously are **infinite in the IR limit**, i.e.,

Proposition II

In a model with SSB sector, the usual IR asymptotic scattering states can not be defined in the full theory for Higgs fields. These fields's quanta are subejct to infinite effective couplings in the IR limit. In standard model, the Higgs particles seem to be IR confined in a formulation constructed with stable parameters only.

This confinement predicted here does not tell us explicitly anything about the theory's short-distance behavior since the EFP is defined in the IR limit. It is quite natural that the mass term and the effective couplings for the Higgs fields remain tractable and well behaved in the short-distance processes and all the conventional calculations and conclusions about the short-distance behavior should remain valid. The origin of the IR singularity of the EFP can be roughly understood in the following way: the effective action $\Gamma(\phi)$ for the QFT should be well defined as a functional of the spacetime dependent expectation value of Higgs fields ($\delta\phi(x)$) as well as all the 1PI Green functions ($\Gamma^{(n)}(x_1, x_2, \cdots, x_n), \forall n \geq 2$). Then the effective vertices in EFP read

$$\Gamma^{(n)}(0, \cdots, 0) = \int \prod_{j=1}^{n} dx_j \Gamma_c^{(n)}(x_1, x_2, \cdots, x_n) \tag{17}$$

where the integrations are over the whole spacetime. Then even if the 1PI n-point functions given in the effective action are well-defined functionals of $\phi(x)$, the infinite range of spacetime integrations might give rise to singular objects. Suppose an n-point function differs a tiny amount at different points of a neighborhood of ϕ, then the infinite spacetime integrations will make this difference explosively amplified, i.e., the left hand side of Eq.(17) will become singular. In other words, the spacetime integration could turn a regular object into a singular one. More spacetime integrations, more singular the effective vertices are, in perfect accordence with the above discussions about the vertices in EFP. Thus, in a sense, despite the IR singularity we might expect the theory be regular at short distance with the Taylor type functional expansion being feasible and hence the Higgs fields may possess scattering states in the short distance, perhaps like quarks somehow. The short-distance behavior is dictated by the original effective action with spacetime dependent field configurations while the IR behavior is dictated by the effective potential with field configurations being constant in spacetime. Of course the short distance should not be so short that the standard model is invalid and new dynamics sets in.

The mass bounds for Higgs particles, in our point of view here, should be bounds for Higgs masses effectively defined in the short distance. Our use of full convex EFP (or equivalently the formulation with stable parameters only) here seems to make us for the first time to be able to predict the confinement (of Higgs fields) from SSB within the conventional QFT frameworks.

One might be supprised at the prediction here of the confinement in the Higgs model. If the prediction is valid, where does it come from given that the Higgs couplings are believed to be not IR singular? First we note that we did not specify the Higgs sector in our dicsussions, only SSB is required. Since the original Higgs model is only one way of realization of SSB in a phenomenological sense, there is no point to extrapolate the running coupling behavior there to all the other formulations realizing SSB. At least we do not know the true underlying theory yet and can not exclude the possibility of Higgs confinement right now. Second, even within the original Higgs model there is the nonconvex piece which is unstable, after these unstable ingredients decay way, the stable dynamics would not be like the original Higgs model any more, and hence there is chance for interactions effectively leading to Higgs confinement or we can expect that the decay mechanism of the unstable modes has something to do with the IR confinement of the stable modes.

It is not clear whether the confinement indicated here is similar to color confinment, as the dominating interactions for the two sectors are different. It is also not clear what the Higgs particles are confined into. We had not made explicit dynamical calculation of the running coupling constants here, but we found some qualitative constraints on the effective coupling constants imposed by very general principles of the theory–SSB and convexity (or equivalently stable parameter formulation), a nonperturbative result. The prediction that the IR confinement of Higgs fields follows from the flavor symmetry breaking (SSB) complies with the well known fact that in some abstract models Higgs and confined phases are indistinguishable [16]. In fact our arguments here add to support that relation between Higgs and confined phases. The present investigation might hint a new scenario for the particle physics due to the scale differences: as the energy goes down, quarks become confined first above Λ_{QCD}, then the Higgs particles become confined at still lower scale. If we still trust the Higgs model with $\lambda\phi^4$ couplings in the short distance (with energy scale no larger than the scale where the model fails, however) and accept the IR property revealed in the convex

EFP (unstable modes removed via Legendre transform), then we roughly have a weak-coupling confining phase with SSB occurring in the meantime. Very recently a weak-coupling realization of confinement and chiral symmetry breaking has been discussed where confinement and SSB seem to concur, the so-called color-flavor locking phenomenon[17]. This, may serve as a third argument in favor of the Higgs confinement in standard model in addition to the two given above.

Given the recent result of Higgs mass range ($m_H = 115^{+116}_{-66} GeV/c^2$, [18]) (in the short distance dynamics), we should be reminded of any possible unconventional properties or aspects of the SSB in addition to the conventional wisdoms in the course of Higgs hunting. The confining picture for Higgs fields here might suggest that we should pay more attention to objects besides normal IR scattering states. Of course the underlying microscopic dynamical mechanisms that lead to SSB together with IR confinement of Higgs particles is still out of our sight. As our investigation only made use of a few general properties (mainly SSB as convexity should be a natural property for theory with stable parameters only), the confinement phenomenon predicted here might be a model independent and universal one somehow. We also wish to mention that it is believed for decades that color confinement in QCD implies chiral symmetry breaking [19], while our investigation here seems to demonstrate a reverse situation for Higgs sector, i.e., symmetry breaking implies (IR) confinement. Both point to a very close relation between SSB and confinement. So further investigations on the subject and its relevance to the quark confinement, especially to the confinement in the supersymmetric gauge theories [20], will be interesting and important. Of course our prediction here based on the EFP approach should be checked independently in other frameworks. We would like to add that the conclusions in SUSY QFT follow from a very simple property–holomorphy of the Wilsonian effective action, while ours follows from a very simple property–convexity of the full effective potential. And our prediction here is by now not in contradiction with the established theoretical and experimental facts, at least in principle.

We would like to say that even one doubts such use of the full EFP, the instability in the nonconvex formulation indicated by Weinberg and Wu's work [10] suggest that quantum theory of the SSB (or Higgs) sector might be far more complicated then traditionally expected. There might be some important new aspects, if not the confining picture predicted here, to be

revealed in the SSB sector of standard model. The use of convex EFP here at least can help to remind us of such possibility about SSB.

4 Digression on Triviality

Now we would like to digress on the triviality issue for a while which is often associated with scalar QFT [21]. Most QFTs known by now are beset with certain kind of ill-definedness somehow. They should in fact be effective theories only valid *within a finite energy range*. There are underlying structures that, if correctly formulated, could remove the ill-definedness in QFTs. This is what is now accepted as standard point of view and closely followed in our approach for renormalization [9]. We had pointed out that in section II, according to the standard point of view, the present QFT formulation amount to be resulted from an illegitimate operation: let the underlying structures vanish before the intermediate quantum processes are fully accounted. This operation then calls for the need of regularizing the theory by hand and then subtracting the divergences afterwards.

This artificiality might make a QFT fail to describe the physics fiathfully, since it has effectively deformed the true underlying structures in a way unknown to us. Such examples are not rare in literature especially in unrenormalizable cases. Thus it is probable that a bad regularization scheme made a theory inconsistent or trivial, due to untamed artificiality introduced by the regularization within the theory's validity realm. Wonderful regularization schemes are rare to find, and the true underlying structures remain elusive to us. Things become worse when one tries to extend the energy scale of the effective QFT to a place where the theory is no longer supposed to be valid. In this case the theory, no matter in what kind of regularization, *should be abandoned and superceded by other effective theories*, there is no point in using and discussing it any more [9]. This time, blames should not be put on the theory, but on the user. Thus, it is important to probe the boundaries where an effective theory fails and keep in mind, when making predictions, these boundaries as well as the influence of the artificiality residing in a regularization scheme.

A truly trivial theory should not be able to yield any nonzero effective interactions at any scale, in any regularization schemes. Once a quantity in a QFT becomes 'trivial' might imply that one had crossed the validity

boundaries of the theory except for the possibility that the theory is truly trivial and totally useless in the traditional sense. In fact no theory is totally useless provided it has been constructed following genuine physical principles and due consistency. (The regularization artificiality should be carefully and effectively removed already). The only problem is that some theories constructed are less predictive or are valid within smaller ranges.

The IR singularity predicted here might make one think that the theory is IR trivial according to conventional wisdom about triviality. In our point of view, since our prediction is based on such a formulation that all the the no unphysical divergence should show up (or a formulation that reasonable procedures removing both UV and IR divergences should have been done) and all the quantum corrections accounted, i.e., a nonperturbative prediction in terms of well-defined parameters, the singularity can not be a signal of triviality in the IR limit. It literally implies that the theory is physically singular in terms of the Higgs fields, but not necessarily IR singular in terms of other fields or parameters, i.e., the objects into which are the Higgses confined. Recall that in QCD, the IR singularity leads us to conclude the color confinement instead of triviality.

5 Summary

Again we note that since our prediction here do not depend on the model specifics, the phenomenon of confinement following from symmetry breaking might be somehow universal. In other words, the underlying dynamics leading to SSB might also dictate the confinement phenomenon. The close relation between quark confinement and chiral symmetry breaking has been interesting theorists for several decades. The prediction here, yet to be checked independently in other approaches, might add to the ongoing interests upon the investigations in SSB and confinement.

In short, we just suggested an alternative angle of looking at the SSB phenomenon. Without doing detailed dynamical calculation, we found some nontrivial consequences following from SSB basing quite general and plausible assumptions, i.e., consistent existence of convex full effective potential or equivalently the existence of a formulation of standard model in terms of stable parameters only. The interesting IR confinement of the fields triggering SSB is not, at least in rough sense, in contradiction with known theoretical

and experimental facts.

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